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Circular Biogas-Based Economy in a Rural Agricultural Setting

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Abstract

This study investigates the application of a circular economy in a rural agricultural setting in Northern Ireland, centered around a typical anaerobic digestion (AD) plant, showing its potential to provide renewable energy for the electricity and transport fuel needs of an average dairy farm and associated milk processing facilities. It was calculated that a typical AD plant has the potential to fuel 22 average sized dairy farms in Northern Ireland, equating to the production, transport, and processing of 51,986 litres of milk per day. The feedstock needs of the AD plant can be provided by the local farming community.

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Keywords: Circular economy; anaerobic digestion; biogas; biomethane; renewable energy; dairy farming

1. Introduction

1.1. Farming in Northern Ireland

Currently, there are just over 24,500 farms in N Ireland, with dairy, beef and sheep being the largest commodity sectors [1]. In N Ireland, over 47,700 people work on farms [1]; this makes up 9.9% of the overall workforce, which

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is above average compared to the rest of the UK, highlighting the value of agriculture to the country and its economy [2]. Agriculture also supports jobs in other sectors, with a further 22,000 people employed directly within the N Ireland food and drink industry [3]. Farming is very important to the UK as a whole, with the industry making major economic contributions both in its own right and as a key supplier to the agri-food industry. In 2015, agriculture contributed around £24 billion of revenues and around £8.5 billion of Gross Value Added (GVA) to the UK economy, with the ratio of the agricultural industry's benefits to the UK economy to its costs to the UK standing at 7.4:1 [2]. In N Ireland, the GVA produced by agriculture in 2015 was £354 million, 4.2% of the overall value of the N Ireland economy [2]. The agriculture industry also contributes to the wider economy, with £486 million in purchases made from other sectors by farming businesses in N Ireland in 2015 [2].

1.2. Emissions due to agriculture

N Ireland, which accounts for just 2.8% of the population of the UK [4], produced ~20.3 million tonnes of CO₂ equivalent in 2014, 4% of total UK greenhouse gas emissions (GHG) [5]. The agricultural sector is the largest contributor to N Ireland's GHGs, accounting for 28% [5]. Emissions are predominantly from livestock (methane) and soils (nitrous oxide), and N Ireland accounts for 8.1% and 7.9% of the UK's emissions of methane and nitrous oxide respectively [5]. Emissions from energy use (12%) are composed of emissions from stationary combustion (10%) and from off-road machinery (90%) [6]. Due to the relative importance of agriculture to the N Ireland economy, agricultural sources accounted for a higher proportion of emissions here than other parts of the UK [5]. The second largest contributor to N Ireland's GHG emissions is the transport sector, which accounted for 21% in 2014 [5]. Transport is closely linked to agriculture, with heavy duty vehicles used both by farmers and to distribute the wide variety of raw materials and products needed by processors and retailers to meet the demands of customers.

The Renewable Energy Directive requires all EU member states to fulfill at least 20% of their energy needs with renewables by 2020, with at least 10% renewable transport fuels [7]. Revised in 2016, the Directive set a new target for 27% of energy needs from renewables by 2030 [7], and for fuels made from wastes/residues to receive double credits [8]. Exploring alternative, environmentally benign and energy efficient systems is therefore important, particularly in the agricultural and transport sectors; one technology that is receiving increased interest is anaerobic digestion (AD). The share of renewable electricity from AD in the UK rose by 40% between 2014 and 2015 [9].

1.3. Anaerobic digestion in Northern Ireland

AD is a process in which organic matter is broken down by micro-organisms in an oxygen-free environment to form biogas and digestate/biofertiliser. The feedstock (organic matter) can include pig or cattle slurry, poultry litter, energy crops such as grass silage, and food waste. Biogas composition is dependent on the feedstock, but is typically ~60% methane (CH₄) and ~40% carbon dioxide (CO₂), with some minor constituents such as water and hydrogen sulphide (H₂S) [10]. The most common use of biogas is directly for combined heat and power (CHP) generation, with the electricity being used on-site and/or injected into the grid. In Europe in 2013, more than 90% of biogas was used for electricity generation [10]. A growing use of biogas is as a road vehicle fuel, which requires the upgrading [11] of biogas to biomethane (typically >97% CH₄) to remove the CO₂ and impurities and to bring it to the same standard as natural gas; the two fuels can be used interchangeably. Biomethane offers the same benefits as natural gas (lower carbon intensity, reduction in emissions of particulate matter) but has a lower carbon footprint if it is sustainably derived from organic materials. Biomethane from animal slurry, for example, offers 84% GHG savings compared to diesel when used as a transport fuel [12], while biomethane from grass offers 75% savings [13].

To reduce N Ireland's dependence on imported fossil fuels (which account for ~90% of total energy demand [6]), incentives and targets have been put in place to increase the proportion of locally sourced renewable energy, including biogas. Around 40 AD plants are either in operation or under construction in N Ireland [14] and, as of 2013, 91 planning applications had been granted for AD plants [6]. All of the plants are electricity production plants, with two producing heat as well as electricity [14]. The feedstock used is mainly derived from agriculture, with a few plants using commercial and/or industrial waste. For natural gas transport fuels to be feasible in N Ireland, biomethane infrastructure is needed. On the island of Ireland as a whole, the natural gas network is extensive [15], but the current grid does not supply many of the key towns in the west and northwest of N Ireland. There is, however, a £250 million

“Gas to the West” project currently under way, which will bring a natural gas supply to these towns [16]. In the Republic of Ireland, Gas Networks Ireland plans to produce a network of 70 compressed natural gas (CNG) stations servicing public transport, haulage and private CNG vehicle operators [17].

1.4. Circular Economy

A circular economy is an alternative to a traditional linear economy (where resources are made, used and then disposed of). In a circular economy resources are kept in use for as long as possible, with the maximum value extracted from them while in use, and materials and resources are recovered and regenerated at the end of each service life [18]. The key principles of a circular economy are to preserve and enhance nature capital, optimise resource yields and foster system effectiveness [18,19]. Rural farming communities are well suited to the application of the circular economy principle. AD and biogas production could be at the centre of a smart sustainable rural energy infrastructure (Fig.1.), with farms supplying crop and slurry feedstock and local industry supplying food waste, to generate electricity and biomethane. This energy can then go back into the local community, fuelling farmyard vehicles and local public and industrial transport, as well as providing electricity to local farms, homes and industry. In turn, the AD digestate can be used as a fertilizer in crop production, and the cycle can continue.

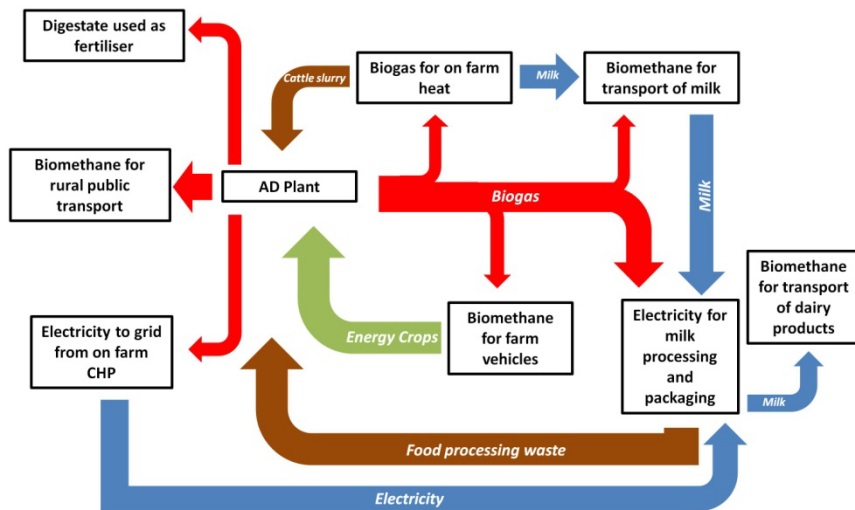


Fig. 1. Circular economy in a smart sustainable rural community.

1.5. Scope

The aim of this paper is to investigate the application of a biogas-based circular economy in a rural agricultural setting in N Ireland. The focus of the study is on agriculture and transport, the two largest contributors to GHG emissions. The study is centred on a typical AD plant and looks at how AD can fuel the agricultural and transport energy needs of typical dairy farms and associated processing facilities.

2. Methodology

By determining the daily energy produced by an AD plant, calculations were made as to how the plant can fuel on-farm milking parlour electricity, on-farm transport fuel, milk tanker transport fuel, and dairy processing electricity. The calculations were based on actual data from a local typically sized AD plant and on a dual fuel trial on a milk tanker conducting its daily run of collection and delivery in the region. This information was supplemented by data from the literature where necessary.

3. Results

3.1. Anaerobic digestion data

AD data were provided by AgriAD Power Ltd., which has developed a 500 kW standalone AD plant at the family dairy farm in Banbridge, N Ireland. The plant is fully operational, having received £3.5 million in investments from the Green Investment Bank. Currently the plant's primary energy output is electricity generation, but the owners are looking to move towards biomethane generation as the gas network in N Ireland improves. The feedstock used in the digester (Table 1) is a combination of grass silage, chicken litter and cattle slurry, all of which is obtained from the family dairy farm and local farms. The usable energy available to be sold (Table 1) is broken down into that available per day, in order to make comparisons to that required for milk production and transport.

Table 1. AD plant characteristics.

Grass Silage Feedstock (t/year)	Chicken Litter Feedstock (t/year)	Cattle Slurry Feedstock (t/year)	Biogas Produced (MJ/day)	Parasitic Demand [20]	Biogas Available (MJ/day)	CHP Availability	Engine Electrical Efficiency	Biomethane Conversion Efficiency [21]
7500	3100	5000	102429	10%	91186	42.1%	91%	89%

3.2. Average Dairy Farm Statistics

In N Ireland there are 2,694 dairy farms, and 317,146 dairy cows in total [1]. There are a small number of dairy cows in small herds on other farm types, but there is no information in literature to say exactly how many. Therefore, for this study it is assumed that all the dairy cows are located in herds on dairy farms and the average dairy herd is taken to be 117.7. This herd size corresponds well to the average herd size of 114 in 2015 [22]. Not all cows in a dairy herd are milk producers, with some of the herd being in calf. From the census [1], with data only available up to 2004, the ratio of cows in milk to those in calf was calculated as 12.4:1. Therefore, the number of dairy cows in milk in the average herd in N Ireland is assumed to be 108.9. The average yield of milk per cow each year is 7,916 litres (in 2014) [22], and therefore a daily yield per cow is 21.7 litres. The daily yield for a typical herd on a N Ireland dairy farm is assumed to be 2,363 litres.

In terms of contributing to AD feedstock, farms have the potential to provide both grass silage and animal slurry. There are 24,528 farms in N Ireland [1], and grassland is the predominant form of land use, with a total area of 800,780 ha [1]. The average grassland area per farm is therefore 32.6 ha. If grassland yields 10 tDS/ha/yr [23], and the dry solids (DS) content of grass silage is 22% [20], the potential from the average grassland farm is 1,482 tonnes of fresh grass silage per year. The slurry potential of the average dairy farm is calculated according to [24,25]. The most common dairy cow in N Ireland is the Holstein-Friesian [26], weighing between 450 and 600 kg [27]. Assuming that there are 117.7 cows in the average dairy herd, the herd's slurry production per month [25] is 190 m³. If the average housing period of a dairy herd is around 5 months [20,28], the yearly available cattle slurry per farm is 950 m³; assuming that slurry has the same density as water (1000 kg/m³), this equates to ~950 tonnes.

The statistics of the average farm in N Ireland (Table 2) are used in the discussion to determine the feedstock potential of the average farm to AD, and to examine the number of farms that can be fuelled by AD.

Table 2. Average N Ireland farm statistics.

Dairy Farm Average				All Farm Averages	
Number of Dairy Farms	Cows in Milk (per farm)	Milk Yield (litres/farm/day)	Cattle Slurry Feedstock (t/farm/year)	Average crop/grass Area (ha)	Grass Silage Feedstock (t/farm/year)
2694	108.9	2363	950	34.6	1482

3.3. Dual fuel trial data – Milk tanker transport fuel requirements

For the dual fuel vehicle trial, conducted by Queen's University Belfast for a local transport logistics company, a Volvo FM13 6X2 tractor unit was fitted with a Clean Air Power [29] CNG dual fuel system. The HGV was monitored on its daily route to collect milk from dairy farms in rural areas. Following the collections, the HGV returned to refuel at the haulage firm base, before travelling to the dairy to deposit the milk payload and then return to base again. Although the quantity of milk collected during the daily pick-up run was not disclosed, the maximum and minimum gross vehicle weights (GVW) were reported. The GVW of the HGV and the empty trailer was 12,500 kg. The vehicle was assumed to be at its daily maximum GVW (42,900 kg) from the last pick-up to the delivery, and the daily milk payload was assumed to be 30,400 kg. Based on an average dairy herd production of 2,363 litres of milk per day (~2,363 kg), the payload is assumed to be collected from 13 dairy farms. The trial was conducted over four days, with journeys taking place on a combination of A and B roads, typical of rural communities in N Ireland. A data logger measured fuel consumption (in diesel litre equivalent). The average overall daily journey (collection and delivery run) of a milk collection and delivery run was 365 km, which required an average energy consumption of 2,925 MJ [30]. The fuel energy required by the milk tanker is therefore 225 MJ/farm/day.

3.4. Dairy farm electricity requirements

It is estimated that the cost of electricity on Irish dairy farms is around 1.5% of the cost price of milk sold [31]. This value is expected to rise due to the introduction of dynamic electricity pricing [32], which will introduce peak and off-peak prices by 2020 in order to discourage energy consumption when energy demand on the national grid is high. It has been estimated that on dairy farms in Ireland, 62% of daily electricity use occurs during the peak hours of 1700-1900 [33]. Electricity consumption is identified as contributing ~25% of energy use along the life cycle of pasture based milk [33]. Upton et al. [33] conducted a study documenting the electricity use, per kilogram of milk sold, averaged across 22 dairy farms in Ireland and N Ireland. The majority of electricity energy use was centered around milk collection, with 31% used for milk cooling, 23% for water heating, and 20% for milking. The remaining electricity was used for water pumping (5%), lighting (3%), and other miscellaneous consumption from winter housing systems, air compressors and backing gates (18%). The study found that the on-farm electrical energy required was 0.3 MJ/kg of milk produced (0.24 MJ/kg used in the milking shed). Therefore, in order to produce the 30,400 kg/day of milk collected and transported during the dual fuel trial, 9,120 MJ of on-farm electrical energy would be required (7,296 MJ of which was used in the milking shed alone). The electrical energy required for on-farm processes is therefore 701.5 MJ/farm/day.

3.5. Dairy farm transport fuel requirements

Upton et al. [33] also looked at transport fuel use across the 22 dairy farms. The study states an overall fuel energy consumption of 0.19 MJ/kg of milk, however, this includes fuel used by contractors, and for transport of feed, fertilisers and forage to the farm. The fuel used on farm was found to account for 66% of the total fuel energy (0.1254 MJ/kg). Of this fuel energy 97.5% was diesel. Therefore, the on-farm diesel fuel energy required on an average dairy farm was 0.1223 MJ per kilogram of milk. In order to produce the 30,400 kg of milk collected and transported during the dual fuel trial, 3,718 MJ of diesel fuel for farming vehicles would be required. The diesel fuel energy required for on-farm vehicle transport is therefore 286 MJ/farm/day.

3.6. Dairy processing electricity requirements

After the milk has left the dairy farm it is transported to a dairy processing facility in order to be converted into various products. In 2012 milk and milk products produced in N Ireland had a market value of £510 million [34]. Modern milk processing facilities now exist in industrialised countries, with both large and small scale plants equipped with modern machinery, and having similar energy requirements [35]. In a modern milk plant, refrigeration plays a significant role in overall energy requirements, accounting for around 40% of the total electrical power consumption [35]. A recent UK study [34] mapped the energy used in refrigeration, from primary chilling through to catering and

retailing, including in modern milk processing plants. The electrical energy required depends on the product being processed. In N Ireland the main milk products are milk powder and cheese [34]. On average in the UK, the total plant electrical energy required in the processing of milk powder is 306 MJ per tonne of milk (85 kWh/t), while for cheese processing, the electrical energy required is 270 MJ per tonne of milk (75 kWh/t) [34]. Therefore, for the 30,400 kg of milk collected and transported during the dual fuel trial, the electrical energy required to process it to powdered milk is 9,302 MJ, or to cheese is 8,208 MJ. For this paper, as a combination of cheese and powdered milk are the primary processed milk products in N Ireland [34], an average value of 8,755 MJ is used. Therefore, the electrical energy requirement in the milk processing plant is 673.5 MJ/farm/day.

4. Discussion

4.1. Fuelling potential of an AD plant for agricultural applications

The previous section of this paper described the daily energy production of a typically sized operational AD plant in N Ireland, and therefore the energy that has the potential to be used in the local community. The AD plant produces 102,429 MJ of biogas per day. As ~10% of this energy is required to meet the parasitic heat demand [20], this leaves 92,186 MJ/day available to be converted to transport fuel energy, in the form of biomethane, and electricity. Currently, all of the biogas produced at this plant is converted to electricity. With the growth of the AD industry in N Ireland, there is a clear possibility that a circular economy can be developed in the farming sector in N Ireland, with many of the processes involved having the potential to be fuelled by the outputs of AD plants. Dairy farming is just one example of this. The daily energy required to fuel on-farm milking parlour electricity, on-farm fuel energy, milk tanker transport fuel, and dairy processing electricity was calculated for a typically sized dairy farm in N Ireland. These energy requirements (Fig. 2) could be fulfilled by AD.

The total fuel energy required for on-farm and milk tanker transport for an average dairy farm in N Ireland was found to be 511 MJ/farm/day. For all electrical processes, both on-farm and in the milk processing plant, 1,375 MJ/farm/day is required. Actual data received from the local AD plant states that the biogas to electricity conversion efficiency is 42.1%, and the CHP engine efficiency is 91%. Therefore, 3,589 MJ/farm/day of biogas is required to meet the on-farm and milk processing electricity demands. The process for the upgrading and compression of biogas to biomethane has an efficiency of 89% [21], therefore, 574.2 MJ/farm/day of biogas is needed to fuel on-farm and milk tanker transport. The total biogas required to fulfil the fuel and electricity needs is 4,163.2 MJ/farm/day. Considering that the available biogas per day of the AD plant is 92,186 MJ, this particular plant has the potential to fuel 22 average sized dairy farms in N Ireland, equating to the production, transport and processing of 51,986 litres of milk per day. Assuming the same output, the 40 AD plants in N Ireland have the potential to provide electricity and transport fuel to around 880 dairy farms, as well as transporting and processing over 2 million litres of milk per day. It is also important to note that the waste digestate can be used on the farms in the form of fertiliser.

4.2. Fuelling potential of agricultural resources for AD feedstock

Not only can AD plants be an important source of energy for fuelling dairy farms, dairy farms can be important for the fuelling of the AD plant. This is a clear display of the circular economy principle. The processes involved in the farming and processing of dairy products produce waste that can then be fed into the anaerobic digester. Cattle slurry is one of the two feedstock constituents of the local AD plant used in this study. Just over five average sized dairy farms would be required to supply the 5,000 tonnes per year of cattle slurry to meet the feedstock needs.

Dairy waste is plentiful in the dairy industry; it contains high levels of organic matter and the disposal of the effluents can cause severe environmental pollution [36]. Whey is the liquid residue of cheese, casein and yoghurt production, and comprises 80-90% of the total volume of milk entering the processing facility [37]. Although it is not used in the AD plant considered in this study, whey can be used as a feedstock for AD [38]. If the 30,400 kg of milk entering the processing plant was processed as cheese, one of the main milk products produced in N Ireland, between 24,320 kg and 27,360 kg of whey would be made as a by-product. An average dairy farm produces 2,363 litres of milk per day, of which 2008.6 litres is whey. Assuming the whey has a total solids content of 3%, of which 87.5% are volatile solids (VS), with a 0.875 m³/kg VS biogas yield and 70% methane content [39], the whey has the potential to produce 32.29 m³ of methane per farm, per day. Assuming that methane has an energy content of 37.78 MJ/m³ [20],

the wasted whey from milk processing has the potential to produce 1,220 MJ/farm/day.

Another of the feedstock constituents of the AD plant in this study is grass silage. The plant requires 7,500 tonnes of grass silage feedstock per year, which could be supplied by five average sized dairy farms in N Ireland.

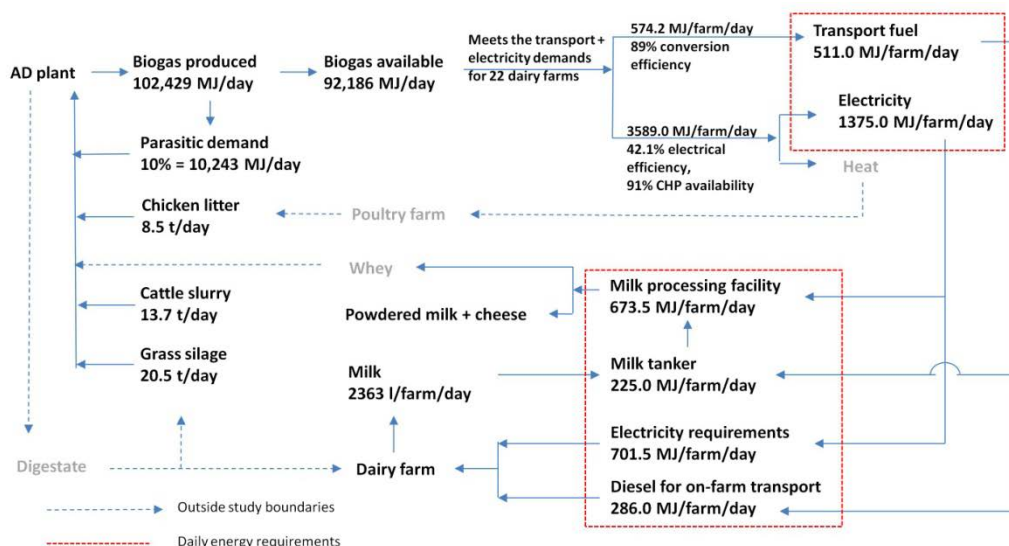


Fig. 2. Circular economy in dairy farming.

5. Conclusions

Anaerobic digestion has the potential to reduce N Ireland's dependence on imported fuels, as well as to help fulfill the requirements of providing increased energy needs through renewables. Production of electricity on-farm, from an AD plant, has the advantages of not only generating energy from a waste product, but also of allowing the farmer to work around a more flexible schedule, without the added cost of peak time usage. Upgraded biogas, biomethane, has a huge potential as a vehicle fuel, and is suitable for injecting into the natural gas grid. Biomethane has a lower carbon footprint than natural gas as it is derived from organic waste. Currently electrical generation is the primary product of AD, however, as the natural gas grid in N Ireland becomes more extensive, there is the possibility for AD plants to shift to biomethane.

This paper shows how an actual AD plant can fuel the electricity and transport energy needs for an average sized dairy farm in N Ireland and the associated milk processing facilities. It was found that the average dairy farm in N Ireland produces ~2,363 litres of milk per day, requiring a total of 1,886 MJ/farm/day in electricity and transport fuel energy. The total biogas required to fulfil the fuel and electricity needs is 4,163.2 MJ/farm/day. The AD plant analysed in this study has the potential to fuel 22 average sized dairy farms in N Ireland, equating to the production, transport and processing of 51,986 litres of milk per day. Not only can AD be important for providing renewable energy for farming, but farming is important for the fuelling of the AD plant. In order to meet the feedstock requirements, it was calculated that five dairy farms per year could provide the grass silage, and five dairy farms per year could provide the cattle slurry. The wasted whey that is a by-product of cheese production can also be used as a feedstock constituent of the AD plant, with the potential to produce 1,220 MJ/farm/day. This study shows how anaerobic digestion can form the centre of a circular economy in a rural agricultural setting in N Ireland.

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